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PATENT

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# BOILING TEMPERATURE DESIGN IN PUMPED MICROCHANNEL COOLING LOOPS

## Related Application

This application claims priority under 35 U.S.C. § 119(e) of the co-pending U.S. provisional patent application Serial Number 60/455,729, filed on March 17, 2003, and titled "Microchannel Heat Exchanger Apparatus with Porous Configuration and Method of Manufacturing Thereof." The provisional patent application Serial Number 60/455,729, filed on March 17, 2003, and titled "Microchannel Heat Exchanger Apparatus with Porous Configuration and Method of Manufacturing Thereof" is hereby incorporated by reference.

## Field of the Invention

This invention relates generally to removal of heat from heat generating devices. More specifically, this invention relates to use of pressure in a heat exchanger within a closed loop cooling system such that fluid temperature will be ideal for removing heat from heat generating devices at a targeted temperature.

## Background of the Invention

A variety of devices and applications are present which require cooling of devices that have very high heat fluxes, such as in the range of 30-1000 W/cm$^2$. These devices include integrated electronic circuits in microprocessors, laser diodes, and power semiconductor devices for control electronics. There have been many solution strategies for cooling these devices.

One solution strategy for cooling a device emitting high heat fluxes includes utilizing a vapor chamber or a heat pipe 10, as shown in Figure 1A. The heat pipe 10 includes a wick structure 14 which draws liquid to the heat source 99 by the use of capillary forces. In particular, as shown in Figure 1A, the liquid evaporates in the wick 14 when heated and the resulting vapor

escapes to the center of the heat pipe 10 where it is propelled to cooler regions for condensation. However, a problem with the geometry of the heat pipe 10 is that the flowrate of the liquid is limited by the capillary pressure available for drawing liquid back into the wick 14. One way to increase the flowrate of liquid through the heat pipe 10 is to make the wick structure 14 thicker. However, thickening the wick structure 14 increases the heat transfer resistance for conduction normal to the wick structure 14 itself, thereby rendering the wick 14 less effective. The temperature rise between the heat inlet and the heat exchange interface would increase if a thickened wick 14 is used, thereby making the heat pipe 10 less effective.

Another solution strategy for cooling the high heat fluxes in the devices is using a microchannel heat sink 20 coupled to a pump 22 and a heat rejector 26, as shown in Figure 1B. This approach in Figure 1B can achieve a much higher liquid flowrate per unit volume than heat pipes 10 (Figure 1A) due to the presence of the pump. This approach increases the heat removal capacity of the heat sink 20 without increasing the system volume. The heat transfer resistance remains low, because the resistance is governed by the small hydraulic diameter and large surface-to-volume ratio of the microchannels 24 in the heat sink 20, which remains the same. Microchannel heat sinks 20 with two-phase boiling convection achieve high rates of cooling with relatively low flowrates through evaporation of the fluid.

However, a problem with cooling a device using these two-phase microchannel heat exchangers is the large pressure gradients that occur along the channels when the liquid begins to boil. It is known that the vapor phase of a substance is much less dense than that of the substance in liquid form. Therefore, for a given pumping power, the vapor phase of the substance will accelerate through a channel by up to a factor of a 1000 times. The acceleration and the resulting shear forces of the vapor substance through the channel dramatically increases the pressure drop along the channel. The large pressure drop in the channel thereby causes two-phase unsteady flow instabilities along the channel. These instabilities are associated with and aggravated by bubbles forming in the flow and large drag forces being produced due to the small dimensions of the channels. The large pressure drop also greatly increases the amount of power

required to pump the liquid through the microchannel heat sink 20. In effect, the microchannel requires more pumping power to cool a device 99, because the boiling of the liquid causes a very large increase in volume flow rate and a large pressure drop within the microchannel heat sink 20.

What is needed is a method of and apparatus for controlling fluid pressure to achieve a targeted boiling temperature within a heat exchanger of a cooling system.

## Brief Summary of the Invention

According to a first aspect of the present invention, a method of cooling a heat-generating device uses a cooling system. The method comprises the steps of: using at least one pump to cause a fluid to flow in at least one heat exchanger; and adjusting a pressure of the fluid to correspondingly adjust a boiling point temperature of the fluid in the at least one heat exchanger. The system can be hermetically sealed. The at least one pump can be electro-osmotic.

The step of adjusting a pressure of the fluid can include adjusting operating conditions of the at least one pump in response to at least one of: changes in pressure of the fluid; changes in temperature of the fluid; changes in temperature of the at least one heat-generating device; and changes in temperature of the at least one heat exchanger. Alternatively, the step of adjusting a pressure of the fluid can include adjusting an orifice coupled to the at least one heat exchanger in response to at least one of: changes in pressure of the fluid; changes in temperature of the fluid; changes in temperature of the at least one heat-generating device; and changes in temperature of the at least one heat exchanger. Further, the step of adjusting a pressure of the fluid can include utilizing a flexible volume reservoir or membrane that controllably expands or contracts. The step of adjusting a pressure of the fluid can comprise adjusting a composition and volume of a gas and liquid introduced during charging of the system. The step of adjusting a pressure of the fluid can also comprise adjusting a pressure of the fluid during charging and sealing of the system.

The method can further comprise the step of providing at least one heat rejector for

rejecting heat from the system. The at least one heat rejector can be situated downstream from the at least one heat exchanger.

The method can further comprise the step of providing a reservoir that accommodates a large volume of gas in the system during boiling. The reservoir can reduce a change in pressure of the fluid that occurs during boiling. The reservoir can be situated downstream of the at least one heat rejector. Alternatively, the reservoir can be situated upstream of the at least one heat rejector. Preferably, the reservoir has a volume region as great as the volume of vapor generated by the at least one heat exchanger during boiling of the fluid. Preferably, the reservoir has an inlet coupled to a fluid outlet port of the at least one heat rejector via a first portion of a fluid transport line and an outlet coupled to a fluid inlet port of the at least one pump via a second portion of the fluid transport line. The reservoir can also be integrated with the heat rejector or the pump.

The fluid can be selected from a group consisting of water, acetonitrile, acetone, N-methylformamide, benzine, ethanol, methanol, any other fluids or a combination thereof. The fluid can also comprise a halocarbon or methane series halocarbon, including trichlorofluoromethane and trifluoromethane. Alternatively, the fluid can comprise a ethane series halocarbon, such as pentafluoroethane, and other halocarbons from the group consisting of methane, ethane, propane, n-butane, 2-methylpropane, isobutane, ethene, ethylene, propene, propylene, and combinations thereof. The fluid can also comprise zeotropic blends, such as R-404A, Azeotropic blends, such as R-500 and R-502, and inorganic fluids, including ammonia and carbon dioxide. Further, the fluid can be a cryogenic fluid selected from the group consisting of hydrogen, parahydrogen, helium, nitrogen, neon, air, oxygen, argon, and combinations thereof.

The method can further comprise the step of providing sensors, such as temperature or pressure sensors, to control the fluid flow from the at least one pump. The sensors can be coupled to the at least one heat exchanger.

The method can further comprise the step of delivering to a catalytic recombiner a gaseous stream containing hydrogen being discharged from a downstream side of the at least one

pump together with an amount of oxygen generated from an upstream side of the at least one pump sufficient to convert the hydrogen to water. The catalytic recombiner can be coupled to an inlet port of the at least one pump.

Brief Description of the Several Views of the Drawings

Figure 1A illustrates a schematic diagram of an existing heat pipe including the wick structure for the liquid and vapor region.

Figure 1B illustrates a schematic diagram of an existing microchannel cooling loop including the pump and the thin channel region for the fluid.

Figure 2 illustrates a cooling system used to cool a heat generating device in accordance with the present invention.

Figure 3 illustrates a schematic diagram of a cooling system under steady state conditions in accordance with the present invention.

Figure 4A is a schematic flow chart illustrating steps of a preferred method of the present invention.

Figure 4B is a schematic flow chart illustrating steps of an alternative method of the present invention.

Figure 5 illustrates a schematic diagram of a preferred embodiment of the reservoir, including a free volume region, in accordance with the present invention.

Figure 6 illustrates a schematic diagram of a cooling system, including an electroosmotic pump that generates hydrogen and oxygen, with means for recombining the gases at the pump inlet.

Figure 7A is a schematic flow chart illustrating steps of an alternative method of the present invention.

Figure 7B is a schematic flow chart illustrating steps of an alternative method of the present invention.

Figure 7C is a schematic flow chart illustrating steps of an alternative method of the

present invention.

Figure 8 illustrates a schematic diagram of an alternative system of the present invention.

## Detailed Description of the Invention

Reference will now be made in detail to the preferred and alternative embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the invention will be described in conjunction with the preferred embodiments, it will be understood that they are not intended to limit the invention to these embodiments. On the contrary, the invention is intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope of the invention as defined by the appended claims. Furthermore, in the following detailed description of the present invention, numerous specific details are set forth in order to provide a thorough understanding of the present invention. However, it should be noted that the present invention may be practiced without these specific details. In other instances, well known methods, procedures and components have not been described in detail as not to unnecessarily obscure aspects of the present invention.

Figure 2 illustrates a schematic diagram of a cooling system 200, which can be a hermetically sealed loop, in accordance with the present invention. The cooling system 200 comprises a microchannel heat exchanger 210, in which a fluid absorbs heat from a heat-generating device 220, a heat rejector 230, which transfers heat from the fluid to a surrounding ambient environment, and a pump 240, which propels the fluid into the heat exchanger 210 and provides a necessary pressure drop for the heat exchanger 210. For purposes of this disclosure, the heat exchanger 210 can contain internal flow regions or microchannels 215 with walls separated by less than 1 mm, with wall separations in a range between 4 micrometers and 500 micrometers. The microchannels 215 of the heat exchanger 210 can be oriented horizontally, vertically or at some other angle, or with combinations of these orientations. Manifolds delivering fluid to the microchannels 215 and removing the fluid from the microchannels 215 can include multiple inlet and outlet regions. The fluid can be defined as any liquid and gas existing

in the system 200. The fluid travels through the system 200 via a fluid transport line 250. When the pump 240 is turned off, pressure will be uniform around the system 200. This uniform pressure, also referred to as a "stationary loop pressure," depends on ambient temperature.

Figure 3 is a schematic diagram of a cooling system 300 under steady state conditions. Immediately after a pump 305 is turned on during steady-state conditions, pressure will be at its lowest at an inlet 310 of the pump 305. Pressure will be at its highest at an outlet 320 of the pump 305. A goal of the present invention is to use pressure to control a boiling point temperature of the fluid in a heat exchanger 330. This pressure, which, under appropriate conditions, will occur within some region within the heat exchanger 330, will influence a maximum temperature in a heat-generating device. When the heat generating device is a semiconductor integrated circuit, this pressure will influence the maximum temperature of elements in the circuit. At low flow rates, the pressure of boiling onset will be nearly equal to an inlet pressure of the heat exchanger 330. At high flow rates, the pressure of boiling onset will be closer to an outlet pressure of the heat exchanger 330. Alternatively, boiling pressure can be intermediate between the inlet pressure and the outlet pressure.

When liquid boils, it absorbs more heat through vaporization than the liquid will absorb when not boiling. In a pumped loop, the boiling fluid creates a vapor whose volume raises the pressure of the loop. By controlling the boiling point temperature of the fluid in a heat exchanger, the system effectively controls a temperature of a heat-generating device. A goal of this invention is to adjust a pressure of the fluid in the heat exchanger to achieve a targeted boiling temperature to effectively cool the heat-generating device to a desired temperature. Specifically, this pressure can be a maximum pressure at which boiling occurs. The pressure of the fluid in the heat exchanger can be adjusted during charging and sealing of the system. The terms charging and sealing, as used in the present invention, can be defined as the act of filling a system with liquid and gas and sealing the system at a targeted pressure. Further, a composition and volume of the liquid and gas introduced during the charging of the system can be adjusted to adjust a pressure of the fluid in the heat exchanger.

In one embodiment of the present invention, a method of cooling a heat-generating device uses a cooling system, as shown in Figure 4A. In the step 400, a pump is used to cause a fluid to flow in a heat exchanger. In the step 410, operating conditions of the pump are adjusted in response to changes in pressure of the fluid to correspondingly adjust a boiling point temperature of the fluid. The method can further include the step of providing a heat rejector for rejecting heat from the system, the heat rejector being situated downstream of the heat exchanger, as shown in Figure 2.

The method can also include the step of providing a reservoir 500, as shown in Figure 5, that accommodates a larger volume of gas in the system 200 (figure 2) generated during boiling. The reservoir 500 can be situated downstream of the heat exchanger 210 (Figure 2) and have a volume region 540 at least as large as the volume of vapor generated by the heat exchanger 210 (Figure 2) during boiling of the fluid at targeted pressure conditions. In a pumped loop, as in Figure 2, boiling fluid creates a vapor whose volume raises the pressure of the entire loop, particularly downstream of the heat exchanger 210 (Figure 2) and the heat rejector 230 (Figure 2). Specifically, the vapor will occupy volume from some region within the heat exchanger 210 (Figure 2), where the fluid starts boiling, and some region within the heat rejector 230 (Figure 2), where the fluid is fully condensed. This region, from boiling onset to full condensation, occupies a volume, V, which can include the fluid transport line 250 (Figure 2) between the heat exchanger 210 (Figure 2) and the heat rejector 230 (Figure 2). Just as occurs in a "pressure-cooking device," the generation of a vapor will increase overall pressure in the loop. The reservoir 500 can reduce a change in pressure of the fluid that occurs during boiling. To achieve a stable operating pressure, the loop must be designed with sufficient free volume before boiling starts to accommodate this increase in volume without exceeding a targeted pressure. Therefore, the free volume 540 of the reservoir 500 includes at least the volume, V, which is equal to the sum of a volume of the heat exchanger 210 (Figure 2) and a volume of the heat rejector 230 (Figure 2) and a volume of the fluid transport line 250 (Figure 2) in between the heat exchanger 210 (Figure 2) and the heat rejector 230 (Figure 2). When the system 200 (Figure 2) is loaded

initially, the free volume 540 can be located anywhere in the loop and will contain low pressure gas.

As shown in Figure 5, the reservoir 500 can have an inlet 510 coupled to a fluid outlet port of the heat rejector 230 (Figure 2) via a first portion of the fluid transport line 250 (Figure 2) and an outlet 520 coupled to a fluid inlet port of the pump 240 (Figure 2) via a second portion of the fluid transport line 250 (Figure 2). Alternatively, the reservoir 500 can be integrated with the heat rejector 230 (Figure 2) or the pump 240 (Figure 2).

As mentioned above, the relevant pressure to be controlled is that in the heat exchanger 210 (Figure 2) at the onset of boiling. Since this targeted pressure will be discerned at some position in the heat exchanger 210 (Figure 2), it will be helpful to minimize pressure drop downstream of the heat exchanger 210 (Figure 2). If there is a large pressure drop downstream of the heat exchanger 210 (Figure 2), it can be difficult to achieve a targeted pressure at boiling onset without requiring a negative (unphysical) pressure at an outlet of the heat rejector 230 (Figure 2). Therefore, this invention covers a variety of methods of achieving low pressure drops in the heat rejector 230 (Figure 2).

In order to achieve a targeted heat source temperature, a boiling point temperature of the fluid in the heat exchanger 210 (Figure 2) can be controlled. This invention covers all fluids operating in a cooling system 200 (Figure 2) with pressure chosen for the boiling point temperature. Preferably, the pressure chosen will be below atmospheric pressure. Preferably, the fluid will consist of water with additives in the cooling system 200 (Figure 2). However, since fluid and fluid mixtures have boiling points that are functions of pressure, many different fluids can be used in the cooling system 200 (Figure 2). For example, the fluid can consist of water, ammonia, acetone, acetonitrile, N-methylformamide benzene, ethanol, methanol or mixtures of multiple substances. In certain cases, the fluid can consist of a nearly pure substance with small quantities of an impurity, such as a buffer, which assists in the operation of other components in the cooling system 200 (Figure 2) such as the pump 240 (Figure 2). In other cases, the fluid can also comprise a halocarbon or methane series halocarbon, including trichlorofluoromethane and

trifluoromethane. Alternatively, the fluid can comprise a ethane series halocarbon, such as pentafluoroethane, and other halocarbons from the group consisting of methane, ethane, propane, n-butane, 2-methylpropane, isobutane, ethene, ethylene, propene, propylene, and combinations thereof. The fluid can also comprise zeotropic blends, such as R-404A, azeotropic blends, such as R-500 and R-502, and inorganic fluids, including ammonia and carbon dioxide. Further, the fluid can be a cryogenic fluid selected from the group consisting of hydrogen, parahydrogen, helium, nitrogen, neon, air, oxygen, argon, and combinations thereof. It should be noted that the fluid can consist of mixtures of all of the above-mentioned fluids.

To help maintain a proper pressure in the heat exchanger 210 (Figure 2), specifically at a location of boiling onset, operating conditions of the pump 240 (Figure 2) flow rate can be adjusted by adjusting a level of an AC voltage 270, DC voltage 275 or other governing input to the pump 240 (Figure 2). This invention covers use of a pump to control a boiling point of the fluid. Sensors 290 can be provided to adjust the fluid flow rate from the pump 240 (Figure 2). The sensors 290 can be positioned downstream and/or upstream of the heat exchanger 210 (Figure 2). Alternatively, the sensors 290 can be temperature sensors downstream and/or upstream of the heat exchanger 210 (Figure 2). The sensors 290 can further be integrated with the heat exchanger 210 (Figure 2) using fabrication techniques.

Although a variety of pumping mechanisms can be used to implement the present invention, pumping of fluids by pumps based on electroosmosis is particularly promising for a hermetically sealed cooling system because it provides robust sealing and reliability. On the other hand, electroosmotic pumps generate gas at an anode and cathode. These gases increase pressure in the system, although this effect can be minimized through efficient recombination of the gases using catalysis. This invention covers a design of a free volume in a pump to include a balance of gases generated at the anode and cathode of the pump to achieve a steady state concentration and pressure contribution due to the generated gases. In one embodiment, as shown in Figure 6, hydrogen generated on a downstream side 610 of a pump 600 travels around a loop 620, through a heat exchanger 630 and heat rejector 640, and back to an inlet side 650 of the

pump 600 where oxygen is generated. The oxygen and hydrogen can recombine at a catalytic recombiner 655 located within a free volume at the inlet side 650 of the pump 600. In this way, the oxygen generated at the inlet side 650 will automatically recombine with the hydrogen introduced at charging, so that pressure buildup can be minimized.

In an alternative aspect of the present invention, as shown in Figure 4B, a method of cooling a heat-generating device using a cooling system is disclosed. In the step 450, a pump is used to cause a fluid to flow in a heat exchanger. In the step 460, an orifice coupled to the heat exchanger is adjusted in response to changes in pressure in the fluid to correspondingly adjust a boiling point temperature of the fluid. The method can further include the step of providing a heat rejector for rejecting heat from the system, the heat rejector being situated downstream of the heat exchanger, as shown in Figure 2.

The present invention discloses a system having at least one orifice, an inlet orifice 280 and an outlet orifice 285, through an inlet port and/or an outlet port of the heat exchanger. The orifices 280 and 285 are configured to direct fluid from a pump to microchannels within the heat exchanger. Orifices are employed for restricting flow rate, and the optimum size for restriction can be determined by employing an adjustable orifice. The orifices can be adjusted or designed such that, during boiling onset within the heat exchanger, there will be a targeted pressure in the heat exchanger during pump operation.

The present invention covers the use of pressure in the fluid to adjust a boiling point temperature of the fluid. However, in two-phase boiling flow, the optimal heat exchanger can use saturation pressure differentials and corresponding saturation temperature differentials. There is a direct relationship between saturation pressure and saturation temperature. When the pressure of a saturated liquid goes up, so does temperature; when pressure goes down, so does temperature. In alternative embodiment of the present invention, as shown in Figure 7A, a method of cooling a heat-generating device using a cooling system is disclosed. In the step 700, a pump is used to cause a fluid to flow in a heat exchanger. In the step 710, operating conditions of the pump are adjusted in response to at least one of: changes in pressure of the fluid; changes

in temperature of the fluid; changes in temperature of the heat-generating device; and changes in temperature of the heat exchanger. The method can further include the step of providing a heat rejector for rejecting heat from the system, the heat rejector being situated downstream of the heat exchanger, as shown in Figure 2.

In another embodiment of the present invention, as shown in Figure 7B, a method of cooling a heat-generating device using a cooling system is disclosed. In the step 750, a pump is used to cause a fluid to flow in a heat exchanger. In the step 760, an orifice is adjusted in response to at least one of changes in pressure of the fluid; changes in temperature of the fluid; changes in temperature of the heat-generating device; and changes in temperature of the heat exchanger. The method can further include the step of providing a heat rejector for rejecting heat from the system, the heat rejector being situated downstream of the heat exchanger, as shown in Figure 2.

In another embodiment of the present invention, as shown in Figure 7C, a method of cooling a heat-generating device using a cooling system is disclosed. In the step 780, a pump is used to cause a fluid to flow in a heat exchanger. In the step 790, a flexible volume reservoir or membrane that controllably expands or contracts is utilized to correspondingly adjust a pressure of the fluid in the heat exchanger.

The present invention further discloses a system having multiple pumps, and/or multiple heat exchangers, and/or multiple heat rejectors. For example, as shown in Figure 8, a cooling system 800 includes one pump 810, three heat exchangers 820, 830 and 840, and one heat rejector 850.

The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of the principles of construction and operation of the invention. As such, references herein to specific embodiments and details thereof are not intended to limit the scope of the claims appended hereto. It will be apparent to those skilled in the art that modifications can be made to the embodiments chosen for illustration without departing from the spirit and scope of the invention.